

σ meson exchange effect on nonmesonic hypernuclear weak decay observables

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We analyze the influence of σ meson exchange on the main nonmesonic hypernuclear weak decay observables: the total rate, Γ_{NM} , the neutron-to-proton branching ratio, $\Gamma_{n/p}$, and the proton asymmetry parameter, a_Λ . The σ meson exchange is added to the standard strangeness-changing weak $\Lambda N \rightarrow NN$ transition potential, which includes the exchange of the complete pseudoscalar and vector mesons octet ($\pi, \eta, K, \rho, \omega, K^*$). Using a shell model formalism, the σ meson weak coupling constants are adjusted to reproduce the recent Γ_{NM} and $\Gamma_{n/p}$ experimental data for ${}^5_\Lambda\text{He}$. Numerical results for the remaining observables of ${}^5_\Lambda\text{He}$ and all the observables of ${}^{12}_\Lambda\text{C}$ decays are presented. They clearly show that the addition of the σ meson, in spite of improving some observables values, is not enough to reproduce simultaneously all the measurements, and the puzzle posed by the experimental data remains unexplained.

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The free decay of a Λ hyperon occurs almost exclusively through the mesonic mode, $\Lambda \rightarrow \pi N$, emerging the nucleon with a momentum of about 100 MeV/c. Inside the nuclear medium ($p_F \sim 270$ MeV/c) this mode is Pauli blocked and, for all but the lightest Λ hypernuclei ($A \geq 5$), the weak decay is dominated by the nonmesonic channel, $\Lambda N \rightarrow NN$, with enough kinetic energy to put the two emitted nucleons above the Fermi surface. The nonmesonic hypernuclear weak decay (NMHWD) offers us a very unique opportunity to investigate strangeness changing weak interaction between hadrons. The NMHWD transitions receive contributions either from neutrons ($\Lambda n \rightarrow nn$) and protons ($\Lambda p \rightarrow np$), with rates Γ_n and Γ_p , respectively ($\Gamma_{NM} = \Gamma_n + \Gamma_p$, $\Gamma_{n/p} = \Gamma_n/\Gamma_p$). Over last three decades a huge theoretical and experimental efforts have been invested to solve an interesting puzzle: the impossibility of the theoretical models in reproducing at the same time experimental values of $\Gamma_{n/p}$ and a_Λ .

From the experimental side there is actually an intense activity, as can be seen in the light of the experiments under way and/or planned at KEK [1], FINUDA [2] and BNL [3]. The preliminary results give a $\Gamma_{n/p}$ ratio value very close to 0.5 [4, 5, 6] and the measurements of a_Λ favour a negative value for ${}^{12}_\Lambda\text{C}$ and a positive value for ${}^5_\Lambda\text{He}$ [5, 6, 7, 8, 9]. On the other hand, from the pioneering work of Block and Dalitz [10] there has been many theoretical attempts dedicated to solve the puzzle. The earlier studies were based on the simplest model of the virtual pion exchange [11]. This model naturally explains the long range part of the two body interaction, and reproduces reasonably well the total decay rate but badly fails in reproducing the other observables. In order to get a better description about short range part of the interaction it has been introduced via: (i) models which in-

clude exchange of different combinations of other heavier mesons, like η, K, ρ, ω and K^* [12]–[19]; (ii) analysis of two nucleon stimulated process $\Lambda NN \rightarrow NNN$ [20, 21]; (iii) inclusion of interaction terms that violate the isospin $\Delta T = 1/2$ rule [22]–[24]; (iv) description of the short range baryon-baryon interaction in terms of quark degrees of freedom [25, 26]; (v) correlated (in the form of σ and ρ mesons) and uncorrelated two-pion exchanges [27]–[30]. We emphasize that none of these models give a fully satisfactory description of all the NMHWD observables simultaneously, in spite that consistent (though not sufficient) increase of $\Gamma_{n/p}$ have been found. Only Jun [24] was able so far to reproduce well the Γ_{NM} and $\Gamma_{n/p}$ (but not a_Λ) data employing, in addition to the one-pion exchange, an entirely phenomenological four-baryon point interaction for the short range part, including the $\Delta T = 3/2$ contribution as well, and fixing the model coupling constants. Concerning the proton asymmetry parameter a_Λ , all existing calculations based on strict one-meson exchange models [14, 15, 16, 18, 19, 26, 31, 32] find values between -0.73 and -0.19 for ${}^5_\Lambda\text{He}$ [33, 34] and, when results are available in the same model, very similar values for ${}^{12}_\Lambda\text{C}$. A recent attempt [34] to explain these discrepancies with the experimental data by means of the FSI effect has failed because, in spite of attenuating the a_Λ value, its effect does not reverse the sign of the parameter. Only two recent theoretical calculations show some agreement with the experimental data: (i) a first application of effective field theory (EFT) to nonmesonic decay [35], and (ii) a very recent extension of the direct-quark interaction model to include σ meson exchange [30]. However, in both cases, a nuclear matter formalism (which does not includes the full contribution of transitions coming from nucleon states beyond the s -shell) is used, and could give therefore a limited description for p -shell hypernuclei or, even worse, for heavier ones.

The EFT approach from Ref. [35] suggests, in order to reproduce the NMHWD data, that the microscopic models should be supplemented by isospin and spin indepen-

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dent central interactions. Motivated by this fact and to set a more detailed description than previous calculations in nuclear matter [30], we analyze the influence of the scalar-isoscalar σ meson exchange over the NMHWD. We will work within the shell model (SM) formalism developed in Refs. [17]–[19], which explicitly includes the contribution of transitions originated from states beyond the s -shell. Therefore, within our model the σ meson is added to the standard strangeness-changing weak $\Lambda N \rightarrow NN$ transition potential already including the exchange of the complete pseudoscalar and vector mesons octet ($\pi, \eta, K, \rho, \omega, K^*$). This model will be referenced as $OCT + S$, to differentiate with our previous $\pi + \eta + K + \rho + \omega + K^*$ model, designed as OCT .

For the pseudoscalar and vector mesons octet, the weak (W) and a strong (S) vertices in the $\Lambda N \rightarrow NN$ decay will be described by means of the same interaction Hamiltonians given in Ref. [15], as it has just been adopted in Refs. [17]–[19]. This lead to the OCT exchange potential

$$V^{OCT}(\mathbf{r}) = \sum_{i=\pi,\eta,K,\rho,\omega,K^*} \bar{V}_i^{(0)}(\mathbf{r}), \quad (1)$$

with $\bar{V}_i^{(0)}(\mathbf{r})$ defined in Ref. [18]. In this equation we have neglected all kinematical and first-order nonlocality corrections because, as it has been extensively discussed in Ref. [18], although their effects can be very important for particular transitions, they do not affect too much the main decay observables. For the σ meson we assume weak (W) and strong (S) coupling Hamiltonians of the form ([30], Eq. (17))

$$\begin{aligned} \mathcal{H}_{\Lambda N \sigma}^W &= G_F \mu_\pi^2 \bar{\psi}_N (A_\sigma + B_\sigma \gamma_5) \phi_\sigma \begin{pmatrix} 0 \\ 1 \end{pmatrix} \psi_\Lambda, \\ \mathcal{H}_{NN \sigma}^S &= g_{NN \sigma} \bar{\psi}_N \phi_\sigma \psi_N, \end{aligned} \quad (2)$$

where ψ_N and ψ_Λ are the baryon fields, ϕ_σ is the meson field, and A_σ and B_σ are the weak parity conserving (PC) and parity violating (PV) coupling constants, respectively, which will be considered as adjustable parameters of the model. For the strong coupling constant we will assume the value $g_{NN \sigma} \simeq g_{NN \pi} = 13.3$. The resulting nonrelativistic one-sigma-exchange potential is

$$V_\sigma(\mathbf{r}) = G_F \mu_\pi^2 g_{NN \sigma} \left[A_\sigma f_C(r, \mu_\sigma) - i \frac{B_\sigma}{2\bar{M}} f_V(r, \mu_\sigma) \boldsymbol{\sigma}_1 \cdot \hat{\mathbf{r}} \right], \quad (3)$$

where μ_σ is the σ meson mass, $\bar{M} = (M_\Lambda + M)/2$ with M and M_Λ being the nucleon and Λ masses, respectively, and all the remaining notation has the same meaning as in Ref. [18]. Thus, we have

$$V^{OCT+S}(\mathbf{r}) = V^{OCT}(\mathbf{r}) + V_\sigma(\mathbf{r}). \quad (4)$$

Using the SM formalism developed in Refs. [17, 18] we evaluate the partial neutron Γ_n and proton Γ_p induced decay rates for ${}^5_\Lambda He$. We include finite nucleon size effect and short range correlations following Ref. [17], and use

TABLE I: Parity conserving and parity violating constants for neutron and proton NMHWD rates of ${}^5_\Lambda He$.

	μ_σ [MeV]		
	550	650	750
a_n^{PC}	0.0096	0.0032	0.0010
b_n^{PC}	1.0806	1.8692	3.4141
c_n^{PC}	0.0000	0.0000	0.0000
a_n^{PV}	0.0022	0.0008	0.0003
b_n^{PV}	7.3380	12.0755	21.0396
c_n^{PV}	0.0508	0.0508	0.0509
a_p^{PC}	0.0192	0.0064	0.0019
b_p^{PC}	1.3623	2.3588	4.2979
c_p^{PC}	0.1422	0.1422	0.1421
a_p^{PV}	0.0014	0.0005	0.0002
b_p^{PV}	12.4826	20.5396	35.8000
c_p^{PV}	0.1398	0.1398	0.1399

a cutoff value $\Lambda_\sigma = 1200$ MeV for the σ meson. The partial decay rates read

$$\Gamma_i = a_i^{PC} (A_\sigma - b_i^{PC})^2 + c_i^{PC} + a_i^{PV} (B_\sigma - b_i^{PV})^2 + c_i^{PV}, \quad (5)$$

where $i = n, p$ and the coefficients a_i^X , b_i^X and c_i^X (which come from SM matrix elements involving the σ exchange) are listed in Table I for different values of the σ meson mass. Solving now the equations system obtained fixing $\Gamma_n + \Gamma_p$ and Γ_n/Γ_p to the ${}^5_\Lambda He$ experimental central values from Ref. [6] (shown in Table II) we obtain the following two sets of solutions for A_σ and B_σ :

$$A_\sigma = 0.67, B_\sigma = 13.39 \text{ and } A_\sigma = 2.08, B_\sigma = 13.08,$$

for $\mu_\sigma = 550$ MeV,

$$A_\sigma = 1.16, B_\sigma = 22.03 \text{ and } A_\sigma = 3.60, B_\sigma = 21.52,$$

for $\mu_\sigma = 650$ MeV and

$$A_\sigma = 2.12, B_\sigma = 38.39 \text{ and } A_\sigma = 6.56, B_\sigma = 37.50,$$

for $\mu_\sigma = 750$ MeV, respectively.

TABLE II: Experimental data for the NMHWD of ${}^5_\Lambda He$ and ${}^{12}_\Lambda C$ (total width is in units of $\Gamma_0 = 2.50 \times 10^{-6}$ eV).

Observable	${}^5_\Lambda He$	${}^{12}_\Lambda C$
Γ_{NM}	0.424 ± 0.024 [6] 0.41 ± 0.14 [36]	0.940 ± 0.035 [6] 1.14 ± 0.2 [36]
$\Gamma_{n/p}$	0.39 ± 0.11 [4] $(0.45 - 0.51) \pm 0.15$ [5] $0.45 \pm 0.11 \pm 0.03$ [6] 0.93 ± 0.55 [36]	— $0.87 \pm 0.09 \pm 0.21$ [5] $0.56 \pm 0.12 \pm 0.04$ [6] $1.33^{+0.12}_{-0.81}$ [36]
a_Λ	$0.07 \pm 0.08^{+0.08}_{-0.00}$ [5] $0.11 \pm 0.08 \pm 0.04$ [6, 7] 0.24 ± 0.22 [9]	$-0.24 \pm 0.26^{+0.08}_{-0.00}$ [5] $-0.20 \pm 0.26 \pm 0.04$ [6, 7] —

Following, we evaluate a_Λ for ${}^5_\Lambda\text{He}$ using the SM formalism recently developed in Ref. [19]. We get

$$a_\Lambda = (k_1 A_\sigma B_\sigma + k_2 A_\sigma + k_3 B_\sigma + k_4)/\Gamma_p, \quad (6)$$

where the constants k_i (containing the SM information) will be given below for a particular value of the σ meson mass. Numerical results obtained with the fixed values of the weak coupling constants have been collected in Table III, together with the predicted values of all the observables for the p-shell ${}^{12}_\Lambda\text{C}$ hypernucleus.

TABLE III: Hypernuclear weak decay observables for the two sets of coupling constants, for each μ_σ (Γ_{NM} is given in units of $\Gamma_0 = 2.50 \times 10^{-6}$ eV).

μ_σ [MeV]	A_σ	B_σ	${}^5_\Lambda\text{He}$			${}^{12}_\Lambda\text{C}$		
			Γ_{NM}	$\Gamma_{n/p}$	a_Λ	Γ_{NM}	$\Gamma_{n/p}$	a_Λ
—	0	0	0.720	0.329	-0.507	1.166	0.267	-0.508
550	0.67	13.39	0.424	0.450	-0.326	0.776	0.427	-0.322
550	2.08	13.08	0.424	0.450	-0.326	0.793	0.435	-0.348
650	1.16	22.03	0.424	0.450	-0.326	0.771	0.421	-0.323
650	3.60	21.52	0.424	0.450	-0.362	0.786	0.428	-0.344
750	2.12	38.39	0.424	0.450	-0.326	0.767	0.416	-0.324
750	6.56	37.50	0.424	0.450	-0.362	0.780	0.423	-0.342

They clearly show that our results are not sensible to the particular μ_σ , A_σ and B_σ selected set, because in all cases our $OCT + S$ model predicts the values $a_\Lambda({}^5_\Lambda\text{He}) \simeq -0.34$, $\Gamma_{NM}({}^{12}_\Lambda\text{C}) \simeq 0.78$, $\Gamma_{n/p}({}^{12}_\Lambda\text{C}) \simeq 0.43$ and $a_\Lambda({}^{12}_\Lambda\text{C}) \simeq -0.33$. This evidences the fact that these three variables are strongly correlated between them and shows the stability of our results, as was the case with the inclusion of the σ meson in πN scattering calculations [37]. A straightforward comparison of $OCT + S$ results with the OCT ones shows that the inclusion of the σ meson reduces the results for Γ_{NM} by $\sim 40\%$. In addition, the neutron to proton branching ratio $\Gamma_{n/p}$ is increased $\sim 36\%$. These last two effects are obtained since the σ meson strongly reduces the PV contribution of the proton induced decay, as can be seen from Eq. (5) and from the fact that $B_\sigma \simeq b_p^{PV}$. This effect can also be observed from Table IV.

TABLE IV: Comparison of partial rates contributions within OCT and $OCT+S$ models for $\mu_\sigma = 550$ MeV, $A_\sigma = 0.67$ and $B_\sigma = 13.39$ (in units of $\Gamma_0 = 2.50 \times 10^{-6}$ eV).

Model		Γ_n^{PC}	Γ_n^{PV}	Γ_p^{PC}	Γ_p^{PV}
${}^5_\Lambda\text{He}$	OCT	0.011	0.167	0.178	0.364
	$OCT+S$	0.002	0.130	0.151	0.141
${}^{12}_\Lambda\text{C}$	OCT	0.024	0.222	0.296	0.624
	$OCT+S$	0.005	0.227	0.251	0.293

However, in spite this meson helps to bring near zero the asymmetry a_Λ (increasing it $\sim 35\%$), its effect is not enough to reverse the sign of the parameter, as required

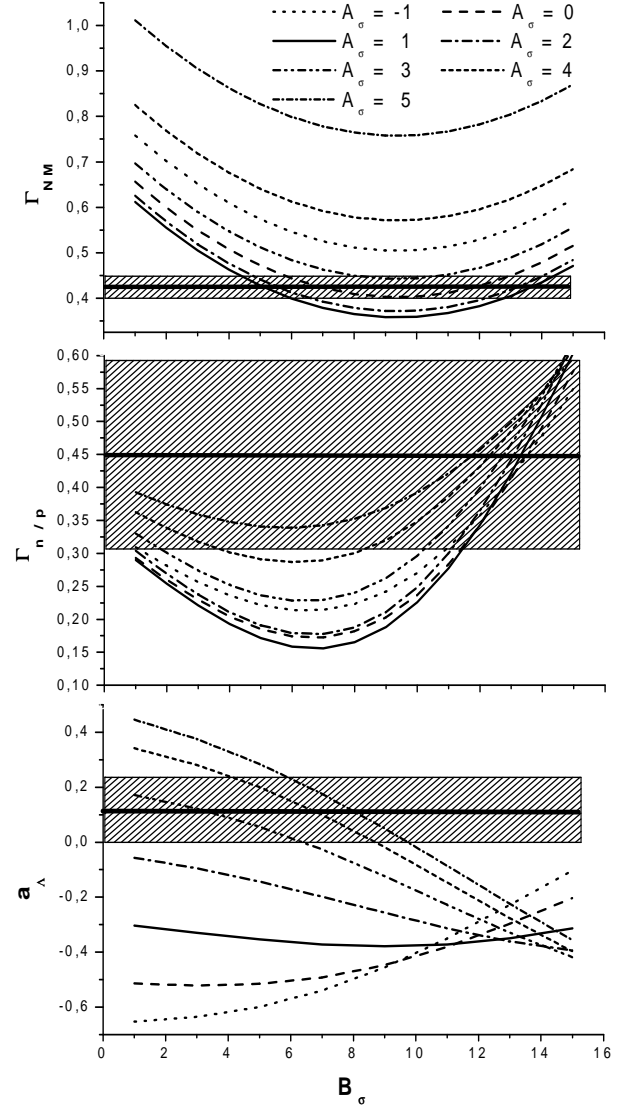


FIG. 1: B_σ dependence of the ${}^5_\Lambda\text{He}$ decay observables, for some particular fixed values of A_σ and for $\mu_\sigma = 550$ MeV. The shaded region stands for the experimental values [6] with error bars.

in the case of ${}^5_\Lambda\text{He}$ hypernucleus. This can be understood noting that, for example for $\mu_\sigma = 550$ MeV, we have $k_1 = -0.010$, $k_2 = 0.127$, $k_3 = 0.014$ and $k_4 = -0.275$. Thus, the strong B_σ and weak A_σ coupling constants required to increase the $\Gamma_{n/p}$ ratio, makes not possible to reverse the a_Λ sign, at least within the implemented hypernuclear model. For the p-shell ${}^{12}_\Lambda\text{C}$ hypernucleus our result is consistent with the experimental data, which have large error bars.

In order to illustrate the A_σ and B_σ dependence of the NMHWD observables, we present in Fig. 1 our results for ${}^5_\Lambda\text{He}$, using $\mu_\sigma = 550$ MeV. This figure shows that within our $OCT + S$ model a bigger value for A_σ and a smaller for B_σ are necessary for reversing the asymmetry sign; however, this leads to overestimate the total rate

Γ_{NM} and strongly underestimate the ratio $\Gamma_{n/p}$. Thus, the $OCT + S$ model implemented with the SM formalism shows that the inclusion of the σ meson is not enough to reproduce simultaneously all the data, specially the positive proton asymmetry value for ${}^5_{\Lambda}He$.

Summarizing, we have made an analysis of the σ meson contribution to the NMHWD observables in the framework of a SM formalism [17]–[19], which includes carefully the effect of the p-shell state decays, both in the partial decay rates as in the asymmetry parameter evaluation. From our results we conclude that, in spite that the σ meson contributes reducing the total decay width Γ_{NM} and increasing the neutron to proton branching ratio $\Gamma_{n/p}$, it is not enough to reproduce the more recent experimental data on the asymmetry. In fact, in the case of the s-shell ${}^5_{\Lambda}He$ hypernucleus, is not possible to reverse the sign of a_{Λ} , while for the p-shell ${}^{12}_{\Lambda}C$ hypernucleus we have obtained a better agreement. Another remarkable characteristic shown by our results is to corroborate the theoretical expectation that a_{Λ} should have only a moderate dependence on the particular hypernucleus consid-

ered, as can be seen from Table III. We suggest two possible alternatives for future work: (i) additional degrees of freedom should be added in our SM formalism to improve the description of the experimental data, for example $\Delta I = 3/2$ contributions in the same footing of Ref. [30] (but now in a finite nucleus scheme) where a better agreement has been obtained for ${}^5_{\Lambda}He$; (ii) to introduce a different decay mechanism for s and p-shell hypernuclei, beyond the Born approximation. Finally, in spite of the uncertainties on the σ meson properties, from the results presented in Table III we have observed that our results are almost independent of the particular choice for the σ mass, and we have clearly shown that the effects of an isoscalar central spin-independent interaction included through the σ meson would not be enough to reproduce simultaneously all the NMHWD observables, without additional changes in the nuclear model and/or the decay mechanism.

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